TRAVEL TIMES FROM BLASTS IN SOUTHERN CALIFORNIA*

By B. Gutenberg

ABSTRACT

Seismograms recorded from a blast of about 70 tons of Du Pont "Nitramon" in tunnels at a quarry near Corona, southern California, are discussed. Arrival times of P waves indicate a velocity of between 5.7 and 6.0 km/sec. in the upper 6 km. of the region, and a velocity of about 6½ km/sec. at a depth of 10 km. The Mohorovičić discontinuity is at a depth of the order of 40 km. The velocity below it is 8.1 to 8.2 km/sec. The amplitudes of S waves are only slightly more than one-tenth of those in an earthquake having P waves of equal amplitudes. The ratio of the velocity of P to that of the first recognizable S is found between 1.6 and 1.7. The first S waves at distances up to about 140 km. indicate a velocity of transverse waves of about 3¾ km/sec. at a depth of the order of 10 km. A phase with an apparent velocity of about 3½ km/sec. can be traced to more than 400 km. It is followed by several slower phases. On the assumption that the amplitudes of Pn do not differ appreciably from those in an earthquake of the same magnitude, the blast would have had a magnitude of about 4.

On August 6, 3:30:00.0 P.M., P.S.T., one shot of about 70 metric tons of Du Pont "Nitramon," distributed in three tunnels and starting about 100 feet from the entrance, was fired at a quarry of the Minnesota Mining and Manufacturing Company near Corona, southern California (latitude 33° 50′.81 N, longitude 117° 30′.36 W) to break up about half a million cubic yards of dacite porphyry for commercial purposes. Careful preparations were made for the timing and recording of this blast. We had cordial coöperation from all concerned. Staff members of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, headed by Dr. M. Tuve, participated in the arrangements. The late Mr. W. J. Rooney arranged the firing of the blast to coincide with a radio time signal. A portable seismograph of the Seismological Laboratory recorded the explosion at a distance of about 300 meters from the shot point. Longitudinal waves were recorded at the eight permanent and four temporary stations of the Seismological Laboratory as well as at Boulder City, Pierce Ferry, and Overton, and at several portable stations installed by Dr. Tuve. For the latter, no readings are available at the time of writing. Seismograms recorded at the three stations of the Lake Mead Seismological Survey (United States Coast and Geodetic Survey) were kindly furnished by Mr. Frank Werner, and data for Lick Observatory by Dr. Perry Byerly.

Coördinates of the stations and data on the instruments are given in table 1. Observed travel times of phases in the P group are summarized in table 2. In figure 1 the times of the earlier P phases are plotted for distances up to 140 km. after deducting $\Delta/6$ to permit the use of a larger time scale. Times for Pn

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TABLE 1

COÖRDINATES OF STATIONS AND INSTRUMENTS USED

(BZ = short-period Benioff vertical seismograph; BH = corresponding horizontal seismographs; WA = standard short-period Wood-Anderson torsion seismographs; O = other instruments.)

Station	Lat. N	Long. W	Elev.	Instruments
	deg. min.	deg. min.	m.	
Pasadena	34 08.9	118 10.3	295	BZ, BH, WA, O
Mount Wilson	34 13.5	118 03.4	1742	BZ, WA
Riverside	33 59.6	117 22.5	250	BZ, WA
Palomar	33 21.3	116 51.6	1700	BZ, BH
La Jolla	32 51.8	117 15.2	8	BZ, WA
Santa Barbara	34 26.5	119 42.9	100	BZ, WA
Haiwee	36 08.2	117 57.9	1100	BZ, WA
Tinemaha	37 05.7	118 15.5	1180	BZ, WA
Perris	33 46.8	117 14.0	440	BZ
Pomona	34 05.9	117 42.6	350	BZ
Crestline	34 14.6	117 15.7	1400	BZ
El Cajon	32 47.6	116 57.3	135	BH
Boulder City	35 58 51″	114 50 02″	776	BZ, BH
Pierce Ferry	36 07 14″	114 00 16″	417	BZ, BH
Overton	36 31 53″	114 26 35″	395	O

TABLE 2

TRAVEL TIMES OF PHASES IN THE P GROUP OF THE CORONA BLAST RECORDS, BASED ON ORIGIN TIME AT 15:30:00.0 P.S.T.

Station	Δ km.	Travel time in seconds						
Portable	0.3	i 00.3						
Riverside	20.3	i 03.7	i 04.3	i 04.8	e 05.8			
Perris	26.4	i 04.6						
Pomona	33.0	i 06.4	e 07.0	i 08.5				
Crestline	49.6	i 08.8	i 09.6	i 10.8				
Mount Wilson	65.9	i 11.6	i 12.1	i 14.1				
Pasadena	70.0	i 11.9	i 13.3	e 14.5	i 18.4			
Palomar	81.6	i 13.7						
La Jolla	111.6	i 18.5	i 20.5	e 24.5	i 27.5			
El Cajon	124.1	i 20.3	i 20.5	i 21.9	i 28.3	e 31.7		
Santa Barbara	214.1	e 34.1?	i 36.6	e 37.8	e 38.8	i 39.6	e 46.2	
Haiwee	257.5	i 39.4	e 43.3	i 45.2	e 46.8	i 47.8	e 55.7	e 60.2
Boulder City	340.3	i 49.4	e 57.4	e 60.5	e 64.5	e 71.5	i 79.9	
Tinemaha	366.8	i 53.2	e 54.6	e 55.4	i 60.6	i 65.1	i 76.6	
Pierce Ferry	407.2	i 57.7	e 68.4	i 69.1	e 71.7	e 74.0	e 79.5	i 92.0
Overton	408.1		i 58.5	e 69.2				
Lick	539.2		e 74	i 84.4	e 89	i 92.8		

have been plotted elsewhere.[1] Travel times from previous blasting in southern California reported by Wood and Richter (1933),[2] as well as a few unpublished readings by Dr. C. F. Richter from a blast near Colton on November 3, 1949, have been added in figure 1. The combined data include travel times along various azimuths. The agreement between them indicates that no considerable dipping of the layers is to be expected in the area involved.

The times of the first arrivals in figure 1 indicate that at a distance of 50 to 60 km. the apparent velocity of the first P waves increases. The first branch indicates a velocity of between about 5.6 and 6.0 km/sec. The value depends

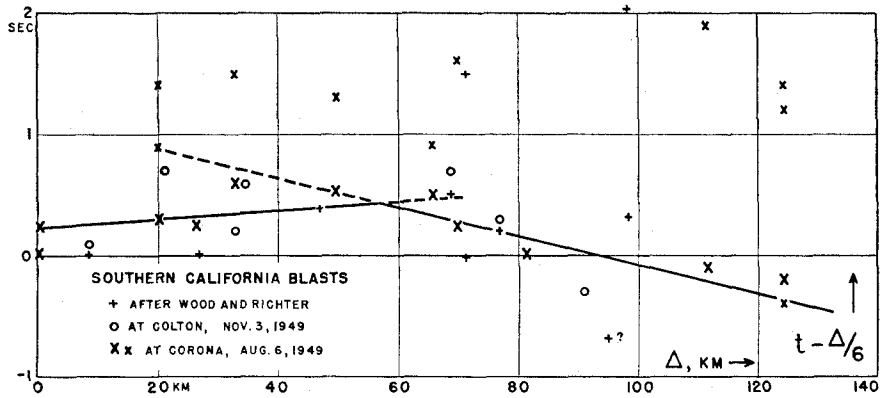

Fig. 1. Travel times of P waves minus Δ/6 from blasts in southern California (Δ = distance in km.).

on the accurate time of the explosion and the effect of the sedimentary and other low-velocity layers near the surface at the source and the stations. The relatively long travel time of 0.3 second to the portable instrument at a distance of about 300 meters is probably mainly an effect of such low velocities, but a noticeable delay between the time signal at 15:30:00.0 and the actual explosion may also be involved. In the Corona blast the combined effect of both is an intercept time of about ¼ second for the travel-time curve of the first P waves (first branch in fig. 1).

For a first calculation of the velocity as a function of depth the two lines indicated in figure 1 have been used. If Δ = distance in km., they correspond to a travel time t given by

$$t = 0.25 + 0.170\,\Delta \qquad \text{and} \qquad t = 1.1 + 0.155\,\Delta \tag{1}$$

respectively. These travel times would indicate that under the uppermost low-

[1] B. Gutenberg, "Revised Travel Times in Southern California," figure 3, *Bull. Seism. Soc. Am.* (in press).

[2] H. O. Wood and C. F. Richter, "A Second Study of Blasting Recorded in Southern California," *Bull. Seism. Soc. Am.*, 23:95–110 (1933).

velocity layers (mainly sediments) there is a layer with a velocity of about 5.9 km/sec. which extends to a depth of about 6 km., where the velocity increases to about 6.45 km/sec. If it is assumed that the transition from the first to the second branch is gradual, the resulting velocity curve shows a corresponding gradual increase in velocity from about 5¾ km/sec. at a depth of 1 km. to 6 km/sec. at a depth of about 4 km., 6.4 km/sec. at about 8 km. depth, and to about 6.5 km/sec. at a depth of 10 km.

Unfortunately, there are no reliable data for distances between about 124 and 257 km. The beginning of the record at Santa Barbara (Δ = 214.1 km.) is not clear. A branch of the travel-time curve indicating velocities of the order

TABLE 3

OBSERVED TRAVEL TIMES t IN SECONDS OF Pn, ASSUMING ORIGIN TIME AT 15:30:00.0 P.S.T.

Station	Δ km.	t	$\Delta/8.2$	$t - \Delta/8.2$
Santa Barbara	214.1	34.1?	26.1	8.0?
Haiwee	257.5	39.4	31.4	8.0
Boulder City	340.3	49.4±	41.5	7.9±
Tinemaha	366.8	53.2±	44.7	8.5±
Pierce Ferry	407.2	57.7	49.7	8.0

of 7 km/sec. has been established in other areas. Seismograms from distances between about 150 and 250 km. are needed for finding of such an additional branch.[3]

Table 3 gives readings for Pn. The beginning is especially clear at Haiwee and at Pierce Ferry. Seismograms of both stations are reproduced in the lower part of figure 2. Table 3 indicates that the apparent velocity of Pn is close to 8.2 km/sec. and the intercept time close to 8 seconds. Pn at Tinemaha shows the delay which is usual for Pn waves which have traveled along northern Owens Valley.

The depth d of the Mohorovičić discontinuity cannot be calculated accurately since the velocity in the depth interval between about 10 km. and the discontinuity is not well known. The order of magnitude of d is 40 km. The

[3] Dr. Tuve and Dr. Tatel have reported their results, at a meeting of the American Geophysical Union held on May 2, 1950 (see abstract in *Trans. Am. Geophys. Union*, 31: 324). They find that "the apparent velocities of the P waves increase from a surface velocity of 5.7 km/sec. to a velocity of 6.8 km/sec. at a depth of about 10 km." Their times of first arrivals on two records from distances of about 8 and 28 km., respectively, fall close to the first branch of the travel-time curve in figure 1. Records at six stations with distances between 70 and 148 km. establish a branch with an apparent velocity of 6.8 to 6.9 km/sec. which also fits the points below the second branch in figure 1. Later readings for some of these stations are close to the solid line (second branch) at distances greater than 70 km. in figure 1. One observation at a distance of 325 km. agrees with the travel times for Pn in table 3 and gives $t - \Delta/8.2 = 7.9$ sec. [This note was added in May, 1950.]

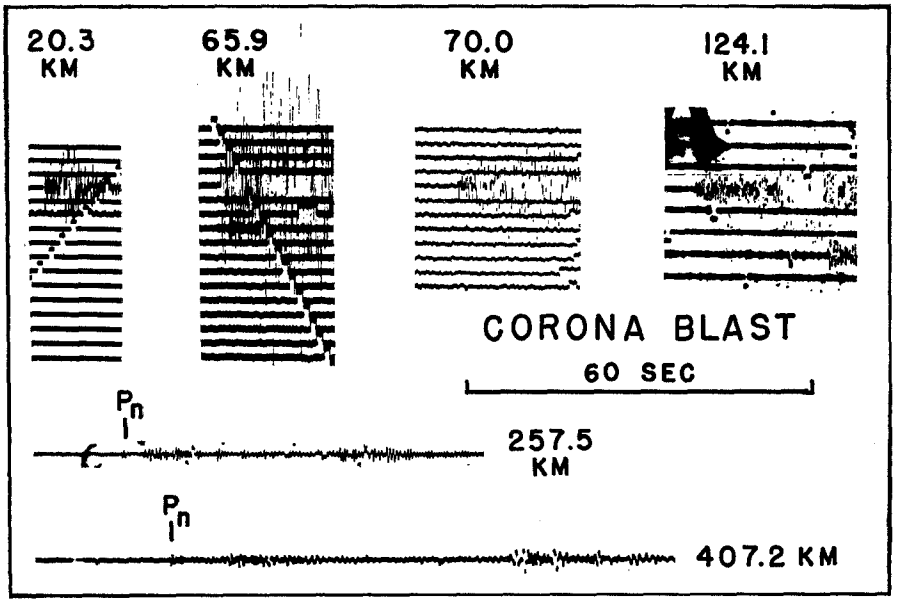

Fig. 2. Corona blast records. Top line, left to right: Riverside, torsion seismograph EW; Mount Wilson, short-period Benioff vertical; Pasadena, short-period Benioff vertical; El Cajon, short-period Benioff EW (recorded on film). Below: Haiwee and Pierce Ferry, short-period Benioff verticals (Pierce Ferry recorded on film).

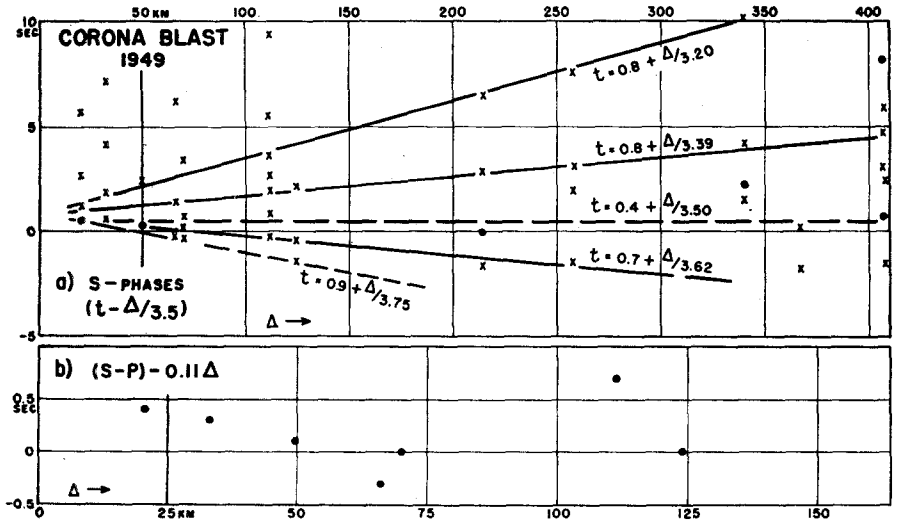

Fig. 3. (*a*) Travel times of S phases minus Δ/3.5 and (*b*) S − P minus 0.11Δ from Corona blast, August 6, 1949 (Δ = distance in km.).

actual velocity V of Pn below this depth is about 0.05 km/sec. smaller than the apparent velocity $\bar{V}$ since

$$\bar{V} - V = \bar{V}d/R \qquad (2)$$

where R = radius of the earth.

Travel times of phases in the S group are given in table 4. It is often not possible to determine the exact beginning of the S group. Travel times of S phases have been plotted in figure 3, *a*, after subtracting $\Delta/3.5$, and differences S − P after deduction of 0.11Δ in figure 3, *b*. They do not indicate the break in two branches near Δ = 50 to 60 km. which has been found for P (fig. 1).

TABLE 4

TRAVEL TIMES OF PHASES IN THE S GROUP OF THE CORONA BLAST RECORDS

Station	Δ km.	Time in seconds						S − P	S/P
Riverside.....	20.3	i 06.3	e 07	e 08½	e 11½			2.6	1.70
Pomona.....	33.0	e 10.0	e 11.2	e 13.6	e 16.6			3.9	1.64
Crestline.....	49.6	i 14.4	i 16.6					5.6	1.64
Mount Wilson..	65.9	e 18.5	i 20.2	i 25	e 34	i 41½		6.9	1.59
Pasadena.....	70.0	i 19.6	i 20.2	i 20.7	e 23.4			7.7	1.65
La Jolla.....	111.6	e 31.5	e 32.7	e 33.8	i 35.5	e 37½	e 41.3	13.0	1.70
El Cajon.....	124.1	e 34.0	e 35.0	i 37.6				13.7	1.68
Santa Barbara.	214.1	e 59.5	i 61.3	e 64	e 67.7				
Haiwee.....	257.5	e 72.1	e 75.5	e 76.7	e 77.7	e 81.2			
Boulder City...	340.3	i 98.7	i 99.4	e 101.4	e 107.5	e 115.4	e 120.5		
Tinemaha.....	366.8	e 103	e 105						
Pierce Ferry...	407.2	i 117	i 119.3	e 121	i 124½	i 127½	i 134½		
Overton.....	408.1	e 115	e 119	e 122½	i 134	e 148			

Since S is probably read too late on many records, the ratio S/P of between 1.6 and 1.7 (last column of table 4) is smaller than the corresponding value of 1.73 found from earthquake records.

If the velocities V and v are constant, in records from a surface source

$$S - P = C\Delta \qquad \text{where} \qquad C = \frac{1}{v} - \frac{1}{V} = \frac{1}{V}\left(\frac{V}{v} - 1\right) \qquad (3)$$

If Poisson's ratio is 0.25, $C = 0.732\ (1/V)$. From figure 3, *b* it follows that C is about 0.112. Since there is a difference in the paths of earthquake waves and blast waves arriving at the same distance, and since C is approximately proportional to $1/V$, it cannot be expected that the value of C in a blast is equal to that in earthquakes, which was found to be about 0.115 at distances up to about 140 km. in southern California earthquakes. In seismograms of the Corona blast recorded at distances greater than about 150 km. the earlier S phases have apparently not been found. Especially, there is no record showing an identifiable Sn phase.

TABLE 5

AMPLITUDES a IN MICRONS AND PERIODS T IN SECONDS FROM CORONA BLAST RECORD

(Log a/T is corrected for the station effect.)

Station	Δ km.	Amplitude a				Period T			Log a/T			
		PH	PZ	PnZ	Max.	P	Pn	Max.	PH	PZ	PnZ	Max.
Riverside	20.3	2	....	....	5	0.1	....	0.2	1.5	....	....	1.6
Mount Wilson	65.9	0.3	1	....	1	0.3	....	0.3	0.0	0.5	....	0.5
Pasadena	70.0	0.2	0.4	....	0.7	0.3	....	0.4	0.0	0.2	....	0.5
La Jolla	111.6	0.1	....	....	1	0.4	....	0.3	−0.4	....	....	0.4
Santa Barbara	214.1	....	....	0.02	0.2	....	0.3	0.5	....	....	−1.2	−0.5
Haiwee	257.5	....	....	0.03	0.2	....	0.5	0.5	....	....	−1.2	−0.5
Tinemaha	366.8	....	....	0.02	0.1	....	0.2	0.5	....	....	−1.2	−1.0

There are phases in several records which create the impression of reflections from discontinuities (such as P33P, etc.),[4] but the data are too scanty for an investigation.

Amplitudes and periods of the main phases have been measured. Essential data are given in table 5. The results for the P waves at the first four stations and for the maximum cannot be easily correlated with corresponding data from earthquake records since the P waves observed at distances less than 150 km. have entirely different paths in blasts and in earthquakes and the maxima are relatively much smaller in blast records than in earthquake records. The amplitudes of Pn should be least affected by the difference in the focal depth and the type of movement near the source in the two cases. However, it must be considered that the energy going into a refracted wave nearly grazing a discontinuity depends on the distance of the source from this discontinuity, a quantity which differs appreciably in blasts and in earthquakes. From comparison with earthquake data it would follow that Pn in the Corona blast had about the same amplitudes as Pn in an earthquake of magnitude 4. In seismograms from near-by earthquakes the maxima are usually in the S group. In the Corona blast records the maxima decrease with distance very nearly as in an earthquake of magnitude 3.1. This indicates that the energy which these phases in the S group have received in the blast is only of the order of magnitude of one per cent of the energy which they would have received in an earthquake with the same energy in Pn.

California Institute of Technology
Pasadena, California
(Division of Geological Sciences, contribution no. 536)

[4] B. Gutenberg, "Reflected and Minor Phases in Records of Near-by Earthquakes in Southern California," *Bull. Seism. Soc. Am.*, 34:137–160 (1944).